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Keywords
Spatial cognition, Spatial memory, Reference frames Hierarchical organization

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Selection of macroreference frames in spatial memory

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Abstract

Spatial memories are often hierarchically organized with different regions of space represented in unique clusters within the hierarchy. Each cluster is thought to be organized around its own microreference frame selected during learning, whereas relationships between clusters are organized by a macroreference frame. Two experiments were conducted in order to better understand important characteristics of macroreference frames. Participants learned overlapping spatial layouts of objects within a room-sized environment before performing a perspective-taking task from memory. Of critical importance were between-layout judgments thought to reflect the macroreference frame. The results indicate 1) that macroreference frames characterize overlapping spatial layouts, 2) that macroreference frames are used even when microreference frames are aligned with one another, and 3) that macroreference frame selection depends on an interaction between the global macroaxis (defined by characteristics of the layout of all learned objects), the relational macroaxis (defined by characteristics of the two layouts being related on a perspective-taking trial), and the learning view. These results refine the current understanding of macroreference frames and document their broad role in spatial memory.

Keywords: Spatial cognition; Spatial memory; Reference frames; Hierarchical organization

Selection of macroreference frames in spatial memory

Location is inherently relative and must be represented within a spatial reference system. Although the number of possible reference frames is infinite, research in spatial cognition has identified several cues that predict which reference frames are most likely to be selected during learning (see McNamara, 2003 for a review). Most of this research on reference frames has focused on learning environments in which all locations are visible from a single vantage point and studied together as a single layout. In contrast, real world spatial learning is often piecemeal, resulting in more segmented spatial memories. For example, a new college student will learn locations of campus buildings as well as locations of stores and restaurants near his or her apartment, and the locations of these learned environments may overlap spatially. Such natural learning often leads to hierarchical representations of space (e.g., Hirtle & Jonides, 1985), consisting of unique clusters of locations within spatial memory. The current research project investigated how such clusters of remembered locations are related to each other in spatial memory, taking an approach similar to that used in past research on reference frame selection.

In a prototypical study on reference frame selection (Shelton & McNamara, 2001), participants studied locations of objects placed on a rectangular rug aligned with the walls of a rectangular room. The study view was either aligned or misaligned with the environmental (rug and room) axes, and all objects were visible from each possible study view. After learning, participants moved to another room to perform judgments of relative direction (JRD) in which they imagined standing at the location of one object, facing a second object, and then pointed to a third object from the imagined perspective. Pointing performance was used to infer the selected reference frame under the assumption that imagined perspectives aligned with the reference frame are relatively easy to retrieve, whereas misaligned perspectives require spatial transformation away from the encoded reference frame which incurs retrieval costs in the form of increased error and latency. When learning occurred from a single view, participants selected a reference frame parallel to the studied view (i.e., pointing errors on the JRD task were lowest when imagining perspectives parallel to the studied view). When learning occurred from two views, one aligned and one misaligned with the axes of the surrounding room, participants selected a reference frame parallel to the aligned view, and performance when imagining perspectives parallel to the misaligned view was no better than when imagining non-experienced views. Those results, together with the body of research on spatial memory, indicate that reference frame selection is influenced by a conjunction of experience-based and environment-based factors (Galati & Avraamides, 2013; Hintzman, O'Dell, & Arndt, 1981; Kelly & McNamara, 2008; Kelly, Sjolund, & Sturz, 2013; Marchette, Yerramsetti, Burns, & Shelton, 2011; Meilinger, Riecke, & Bülthoff, 2014; Mou & McNamara, 2002; Street & Wang, 2014; Werner & Schmidt, 1999; Yamamoto & Shelton, 2005).

In a closely related study, Greenauer and Waller (2010) instructed participants to learn two simultaneously visible layouts made up of small objects placed on the floor. The layouts were visually and semantically distinct, and were also spatially separated such that the global shape of the two layouts together formed an elongated macroaxis. Participants were instructed to learn each layout along a microaxis specific to that layout, and were not given any instructions about whether or how to learn the relationship between the layouts. Participants were then led to another room to perform JRD. Within-layout trials included only objects from one layout, whereas between-layout trials included objects from both layouts. Within-layout trials revealed that participants represented individual layouts using a microreference frame parallel to the instructed microaxis. In contrast, between-layout trials revealed that participants represented the relationship between the layouts using a macroreference frame defined by the global macroaxis of the two layouts together.

The discovery of micro- and macroreference frames (Greenauer & Waller, 2010) was a first step in connecting research on reference frames (e.g., Shelton & McNamara, 2001) with research on hierarchical representations of location (Hirtle & Jonides, 1985; McNamara, 1986; McNamara, Hardy & Hirtle, 1989; Stevens & Coupe, 1978). The current project furthers that research in three ways. First, research on micro- and macroreference frames has been limited to spatially discrete object layouts, whereas clusters found in spatial hierarchies of real environments can be either spatially discrete or overlapping (e.g., Hirtle & Jonides, 1985). To address this, Experiment 1 evaluated the generality of micro- and macroreference frames in the context of overlapping spatial layouts. Second, the macroreference frame seems particularly important for relating two sets of locations that are themselves stored with unique (i.e., misaligned) microreference frames. Aligned microreference frames are already represented within a common framework, and therefore comparison between them should not require additional transformation. This implies that macroreference frames may only be required for layouts with misaligned microreference frames. To evaluate this, Experiment 1 included an experimental manipulation of microreference frame alignment (aligned vs. misaligned). Finally, past research suggests that the global macroaxis formed by the combined set of objects determines macroreference frame selection (Greenauer & Waller, 2010). However, an alternative macroaxis is that formed by the groups being considered at the moment (i.e., the two object layouts being related to one another on a between-layout pointing trial). These two possibilities were indistinguishable in past work using exactly two object layouts. However, when three or more object layouts are considered, the macroaxis could be determined by the global shape of all objects together or the global shape of the layouts relevant to a given judgment. Experiment 2 included three object layouts to evaluate the relevant macroaxis that guides macroreference frame selection.

Experiment 1

Experiment 1 was designed to determine whether macroreference frames characterize overlapping spatial layouts, and whether the macroreference frame is influenced by the alignment of microreference frames. Participants learned the locations of objects within two overlapping layouts that together possessed a global macroaxis (315°; see Figure 1) misaligned with the study view (0°). In two learning conditions participants were instructed to study the objects as two separate layouts along the same microaxis (0°; separate aligned condition) or with misaligned microaxes (0 and 315°; separate misaligned condition). In the third learning condition participants studied the objects as a single layout (0°; combined condition). All participants subsequently performed within- and between-layout JRD. Within-layout judgments were used to verify that participants were able to follow experimenter instructions regarding microreference frame selection, whereas between-layout judgments were used to evaluate the main experimental hypotheses about macroreference frames.

If macroreference frames characterize overlapping location sets, then between-layout judgments in the separate misaligned learning condition should reflect the use of a macroreference frame aligned with the global macroaxis of the two layouts combined (i.e., a 315° reference frame). This would parallel the findings of Greenauer and Waller (2010) who used spatially distinct layouts under otherwise similar conditions (i.e., two layouts with separate misaligned microreference frames).

If macroreference frames exist only for layouts with misaligned microreference frames, then between-layout judgments should differ between the separate aligned and separate misaligned learning conditions. Specifically, between-layout judgments in the separate misaligned condition should reflect a macroreference frame consistent with the global macroaxis (315°), which would be indicated by lower errors in the JRD task when imagining the 315° perspective compared to other perspectives. In contrast, between-layout judgments in the separate aligned condition should be best when retrieval is parallel to the two aligned microreference frames (0°), which would be indicated by lower JRD errors when imagining the 0° perspective as compared to other perspectives. The combined condition provides a comparison in the event that the separate aligned learning condition also leads to selection of a macroreference frame aligned with the global macroaxis. The combined condition should lead to a reference frame consistent with the study view and instructed perspective (0°) because the entire layout is effectively one group, precluding the need for a macro-reference frame. Therefore, the combined condition should result in lower JRD errors when imagining the 0° perspective as compared to other imagined perspectives.

Method

Participants. Fifty-three undergraduate students from Iowa State University participated in exchange for course credit. Participants were randomly assigned to learning condition, and gender was approximately balanced across condition. Data from five participants were removed from all analyses due to angular pointing errors not better than chance, leaving 48 participants (15 in the combined condition, 16 in the separate aligned condition, and 17 in the separate misaligned condition).

Stimuli and design. Stimuli consisted of two overlapping layouts of eight items each (Figure 1). Layouts consisted of categorically distinct objects (toys and office supplies) placed on 12 cm paper disks. Toys were placed on black colored disks, whereas office supplies were placed on white disks. The combined layout of both object sets also had a principal axis[1] along 135-315°. The participant's view during learning was 0°, which was also aligned with the principal axis of the surrounding rectangular room.

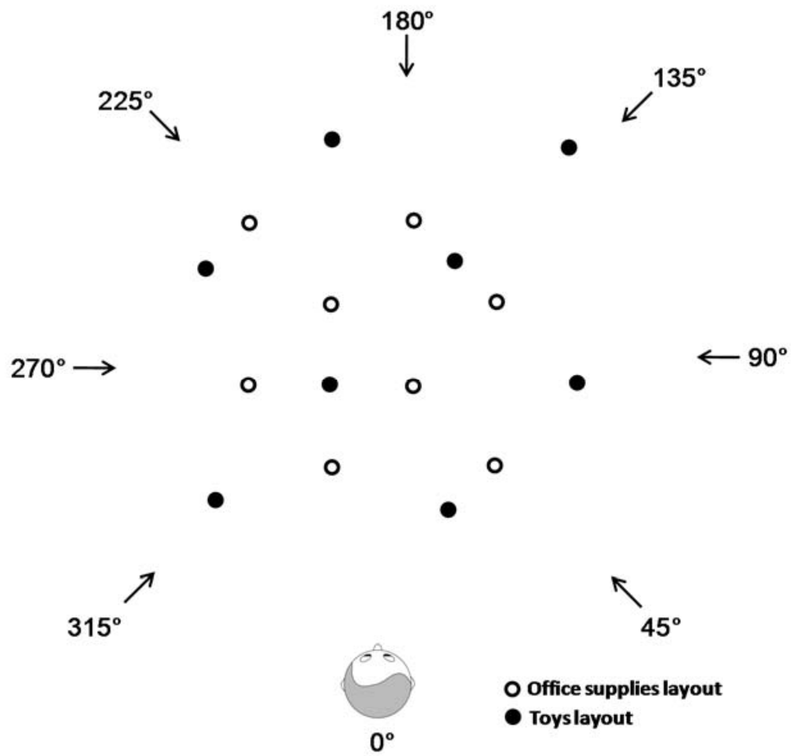

Figure 1. Object locations used in Experiment 1.

Study instructions were manipulated between participants. In the combined condition, participants were instructed to learn all objects as a single layout organized in columns parallel to 0°. In the separate aligned condition participants were instructed to first learn the toy layout

[1] Principal axis was defined as the major axis of an ellipse fit to the object locations, and in Experiment 1 was redundant with a symmetry axis.

along 0° and to then learn the office supply layout along 0°. In the separate misaligned condition participants were instructed to first learn the toy layout along 315°, and to then learn the office supply layout along 0°.

JRD required participants to imagine standing at one object, facing a second object, and point toward a third object from the imagined perspective (e.g., ‘‘Imagine standing at the yo-yo, facing the cow. Point to the dinosaur.’’). The first two objects established the imagined perspective and the third object was the pointing target. Within-layout JRD drew all three objects from either the toy layout or the office supply layout, whereas between-layout JRD drew the standing object and the facing object from unique layouts, and the pointing object was drawn from either layout (e.g., “Imagine standing at the stapler, facing the ball. Point to the mouse.”). For each trial type (within-layout toys, within-layout office supplies, and between layouts), JRD tested eight imagined perspectives spaced every 45° from 0° to 315°. For each imagined perspective, six unique trials were constructed requiring correct egocentric pointing responses spaced every 45° from 0° to 315°. Each participant completed 144 JRD (3 trial types × 8 imagined perspectives × 6 pointing directions). JRD trials were displayed on a computer monitor in white text on black background. Participants responded by deflecting a joystick (Logitech Attack 3) in the intended direction.

The primary independent variables were learning condition and imagined perspective. Pointing error was the primary dependent variable, and pointing latency was also recorded.

Procedure. Participants were blindfolded before being led into the learning environment. After reaching the viewing location, participants were instructed to remove the blindfold. All objects were visible at this point. Depending on learning condition, participants were instructed to study all objects together (combined condition) or to begin with the toy layout (separate aligned and separate misaligned conditions). The experimenter proceeded to name and point to each object in the appropriate order for the participant's condition. Participants were then given 30 seconds to study the objects before replacing the blindfold and attempting to point to and name each object in the instructed order. This study-then-point process was repeated at least four times and was terminated when the experimenter gauged the participant to have successfully learned the layout. Participants in the separate aligned and separate misaligned conditions proceeded to study the office supply layout in the same manner as the toy layout.

After learning, the participant was blindfolded and led to the adjacent test room where the experimenter explained the JRD procedure. The participant then performed example trials using buildings from campus before beginning the randomized JRD set.

Analysis

The focus of the data analysis was to identify the reference frame used to represent a given set of objects (e.g., the toys layout). Past work shows that retrieval is facilitated (lower errors and response times) when imagining perspectives aligned with the encoded reference frame (Shelton & McNamara, 2001). Only theoretically relevant reference frames were evaluated because of the large number of potential comparisons. Specifically, the selected reference frame was most likely to be parallel to 0 or 315° because these were the two directions emphasized by the study view, the principal axis of the layout, and experimenter instruction. Evidence in support of the hypothesized reference frame for a given judgment type (i.e., toys, office supplies, or between-layouts) is signaled by a significant main effect of imagined perspective and significantly better performance from the hypothesized perspective compared to all other perspectives.

Results

Absolute pointing error was calculated as the absolute difference between the correct pointing direction and the pointing response. Pointing latency was calculated as the difference between the time when text appeared on the screen and when a pointing response was recorded. Analyses focused on the effect of imagined perspective on pointing error and latency. Therefore, data from the eight repeated trials for each imagined perspective were averaged together prior to analysis. There was no evidence of speed-accuracy tradeoff. The within-participant correlation between error and latency was significantly positive (M=0.132, SE=0.032), $t(47)=4.08$, $p<.001$. Pointing error was more responsive to the independent variables than was pointing latency, so the focus is on pointing error. Pointing latency results are included as Supplemental Material.

Absolute pointing error is shown in Figure 2 as a function of imagined perspective. When participants learned the objects as a single layout (combined condition), they were best at imagining the instructed perspective regardless of the tested layout (i.e., toys, office supplies, or between-layouts). When participants learned the objects as separate layouts along aligned axes, (separate aligned condition), they were best at imagining the instructed perspective for individual layouts (toys and office supplies) but were best at imagining the perspective aligned with the global macroaxis for between-layout judgments. When participants learned the objects as separate layouts along misaligned axes (separate misaligned condition), they were best at imagining the instructed perspective for the office supplies layout, were equally able to imagine all perspectives for the toys layout, and were best at imagining the perspective aligned with the global macroaxis for between-layout judgments. These conclusions were supported by statistical analyses.

Absolute pointing error was analyzed in a mixed-model ANOVA with terms for imagined perspective (0, 45, 90, 135, 180, 225, 270, and 315°), layout (toys, office supplies, and between layouts), and learning condition (combined, separate aligned, and separate misaligned). Significant main effects of imagined perspective, $F(7,315)=18.44$, $p<.001$, $\eta_p{}^2=.29$, and layout, $F(2,90)=54.97$, $p<.001$, $\eta_p{}^2=.55$, were qualified by a significant interaction between imagined perspective and layout, $F(14,630)=3.98$, $p<.001$, $\eta_p{}^2=.08$, as well as a three-way interaction of imagined perspective, layout, and condition, $F(28,630)=1.94$, $p=.003$, $\eta_p{}^2=.08$.

In light of the significant three-way interaction, each layout was analyzed in a separate mixed-model ANOVA with terms for imagined perspective and condition. For the office supplies layout, only the main effect of imagined perspective was significant, $F(7,315)=13.32$, $p<.001$, $\eta_p{}^2=.23$, and there was no significant interaction. Pointing error (averaged across condition) when imagining the 0° instructed perspective was numerically lower than any other imagined perspective and statistically lower than the pointing error for all other imagined perspectives combined (0°: $M=25.32$, $SE=1.74$; All other perspectives: $M=40.59$, $SE=1.63$), $F(1,47)=43.12$, $p<.001$, $\eta_p{}^2=.48$.

For the toys layout, a significant main effect of imagined perspective, $F(7,315)=12.36$, $p<.001$, $\eta_p{}^2=.22$, was qualified by a significant interaction between imagined perspective and condition, $F(14,315)=1.77$, $p=.042$, $\eta_p{}^2=.07$. In the combined and separate aligned conditions, pointing error when imagining the 0° instructed perspective was numerically lower than any other imagined perspective and statistically lower than all other imagined perspectives combined (Combined condition 0°: $M=21.78$, $SE=2.27$; Combined condition all other perspectives: $M=35.64$, $SE=2.51$; $F(1,14)=19.37$, $p=.001$, $\eta_p{}^2=.58$; Separate aligned condition 0°: $M=24.66$, $SE=2.17$; Separate aligned condition all other perspectives: $M=41.39$, $SE=3.52$; $F(1,15)=46.56$,

p<.001, η_p^2=.76). In the separate misaligned condition, pointing error when imagining the 315° instructed perspective was numerically lower than any other imagined perspective but was not significantly lower than all other imagined perspectives combined nor the 0° studied perspective alone.

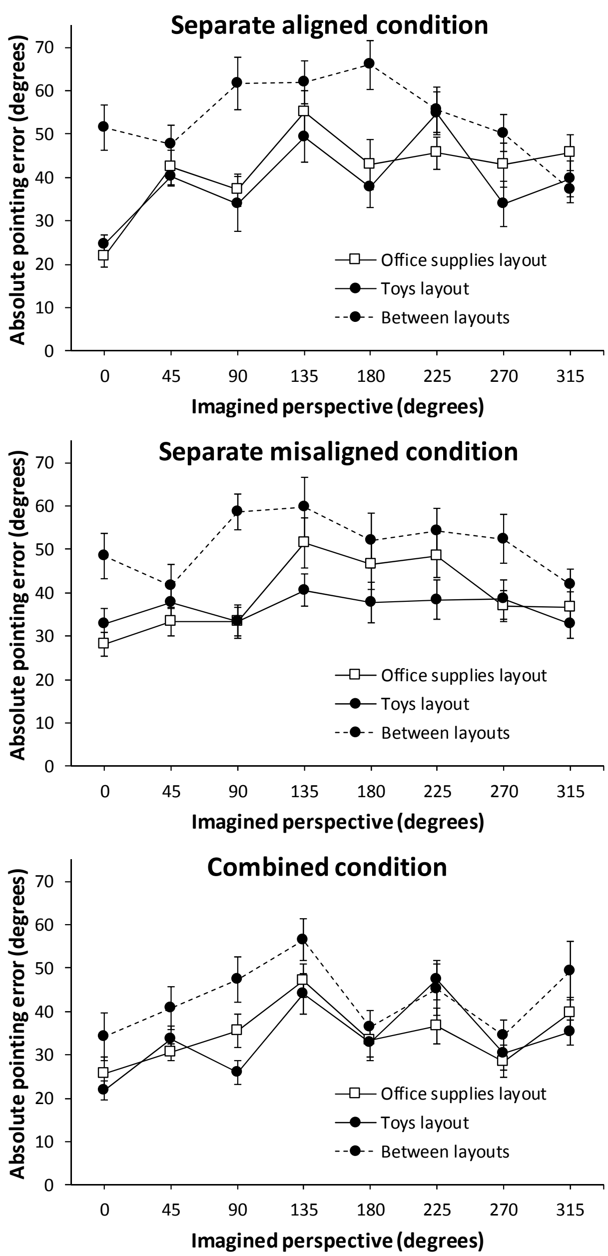

Figure 2. Pointing error in Experiment 1 as a function of imagined perspective. Error bars represent +/- 1 SEM.

For between-layout judgments, a significant main effect of imagined perspective, $F(7,315)=6.19$, $p<.001$, $\eta_p^2=.12$, was qualified by a significant interaction between imagined perspective and condition, $F(14,315)=2.20$, $p=.008$, $\eta_p^2=.09$. In the combined condition, pointing error when imagining the 0° perspective ($M=34.12$, $SE=5.53$) was numerically lower than any other imagined perspective and statistically lower than all other imagined perspectives combined ($M=44.31$, $SE=3.40$), $F(1,14)=5.87$, $p=.03$, $\eta_p^2=.30$. In the separate aligned and separate misaligned conditions, pointing error when imagining the 315° perspective (aligned with the global macroaxis) was numerically lower than any other imagined perspective and statistically lower than all other imagined perspectives combined (Separate aligned condition 315°: $M=37.22$, $SE=3.11$; Separate aligned condition all other perspectives: $M=56.33$, $SE=2.74$; $F(1,15)=35.91$, $p<.001$, $\eta_p^2=.71$; Separate misaligned condition 315°: $M=41.82$, $SE=3.76$; Separate misaligned condition all other perspectives: $M=52.48$, $SE=3.84$; $F(1,16)=7.04$, $p=.017$, $\eta_p^2=.31$).

Discussion

Experiment 1 was designed to determine whether macroreference frames characterize overlapping spatial layouts, and if so, whether the macroreference frame is influenced by alignment of microreference frames. Participants in the separate aligned and separate misaligned conditions selected a macroreference frame parallel to the global macroaxis that characterized the two layouts together. Furthermore, between-participant manipulation of microreference frame alignment did not affect the selected macroreference frame. These results indicate that macroreference frames characterize overlapping spatial layouts, can be independent from microreference frames, and are used regardless of microreference frame alignment. Together these results indicate a rather broad role for macroreference frames. The macroreference frame identified in the separate aligned condition was particularly surprising because a macroreference frame seems unnecessary when the individual layouts are represented in aligned reference frames.

Participants in the separate misaligned condition were instructed to learn the toys layout along the 315° perspective, whereas participants in the separate aligned and combined conditions were instructed to learn the toys layout along the 0° (studied) perspective. The results indicate that participants in the separate misaligned condition organized their memories for the toys layout differently than did participants in the separate aligned and separate misaligned conditions. However, it also seems that participants in the separate misaligned condition were unable to reliably structure their memory for the toys layout around a 315° reference frame, leading to equivalent performance when imagining the 0° and 315° perspectives. This result diverges from results reported by Mou and McNamara (2002) in which participants were able to reliably adopt a non-egocentric reference frame. Participants in that study learned a single layout, and learning two layouts using misaligned reference frames may be more challenging. However, the results do not seem to support this hypothesis. Specifically, overall error when recalling the toys layout was not higher for those in the separate misaligned condition compared to the separate aligned condition, as might be expected if the task in the separate misaligned condition were simply more difficult due to the misaligned microreference frames. It is also possible that some participants in the current study were able to follow the instructions and others were unable to adopt the 315° reference frame. However, participants in the separate misaligned condition who apparently did represent the toys layout using a 315° reference frame performed no better or worse overall than those who represented the toys layout using a 0° reference frame when making judgments about the toys layout, and also did not differ when making judgments about the office supplies layout nor between-layout judgments (detailed analysis are included as Supplemental Material). Regardless, learning instructions in the current study affected both micro- and macro-reference frame organization.

Experiment 2

Experiment 2 explored factors that could determine macroreference frame selection, with an emphasis on defining the relevant macroaxis. One possible macroaxis is defined by the set of all learned objects in the environment, referred to as the global macroaxis. Another possible macroaxis is that defined by the object sets being related to one another for a given spatial task, referred to as the relational macroaxis. Greenauer and Waller (2010) used two spatially distinct layouts, so the relational and global macroaxes were identical. In Experiment 2 of the current project, a third object layout (see Figure 3) was included in order to form separate predictions based on global and relational macroaxes. If the macroreference frame is determined by the relational macroaxis, then judgments between the toys layout and the office supplies layout should reflect a 270° macroreference frame (i.e., lower JRD errors when imagining the 270° perspective as compared to other perspectives) and judgments between the toiletries layout and the toys layout should reflect a 0° macroreference frame (i.e., lower JRD errors when imagining the 0° perspective as compared to other perspectives). However, if the macroreference frame is determined by the global macroaxis then between-layout judgments should reflect a 315° macroreference frame regardless of which two layouts are being compared (i.e., lower JRD errors when imagining the 315° perspective for all between-layout judgments).

Participants studied three layouts under conditions similar to the separate aligned condition in Experiment 1 and subsequently made between-layout judgments involving two layouts on a given trial. Only between-layout judgments were tested because the focus of

Experiment 2 was on factors that influenced the macro-reference frame, and because the results of Experiment 1 and Greenauer and Waller (2010) indicate that micro-reference frame organization does not affect macroreference frame selection. Furthermore, only theoretically relevant perspectives were tested, specifically those aligned with the relational (0 and 270°) or global (315°) macroaxes. This was done because of the more narrow focus of Experiment 2, and because using the same locations from Experiment 1 while subdividing it into three layouts restricted the number of possible perspectives that could be tested.

Method

Participants. Thirty-three undergraduate students from Iowa State University participated in exchange for course credit. None reported having participated in Experiment 1. Data from two participants were removed from all analyses due to angular pointing errors not better than chance.

Stimuli and Design. The same locations used in Experiment 1 were used in Experiment 2 but object identities and groups were modified to create three layouts (Figure 3). The three layouts consisted of toys on black disks, office supplies on white disks, and toiletries on yellow disks. The participant's view during learning was 0°, which was also aligned with the principal axis of the surrounding room.

Testing included between-layout JRD only. Furthermore, JRD tested just two layout pairs, 1) toys and office supplies and 2) toiletries and toys. These pairs were chosen because their relational macroaxes[2] were quite similar to perspectives that could easily be tested using JRD. The toys and office supplies layouts were defined by a relational macroaxis of 258° and JRD created to test this relational macroaxis tested the 270° imagined perspective. The toiletries

[2] Relational and global macroaxes were defined as the principal axis of an ellipse fit to the relevant object locations.

and toys layouts were defined by a relational macroaxis of 8° and JRD created to test this relational macroaxis tested the 0° imagined perspective. The global macroaxis was 315° regardless of the layout pairs tested. The toiletries and office supplies pair was excluded from testing because the relational macroaxis between those two layouts is nearly parallel to the global macroaxis, and therefore those judgments would not be diagnostic.

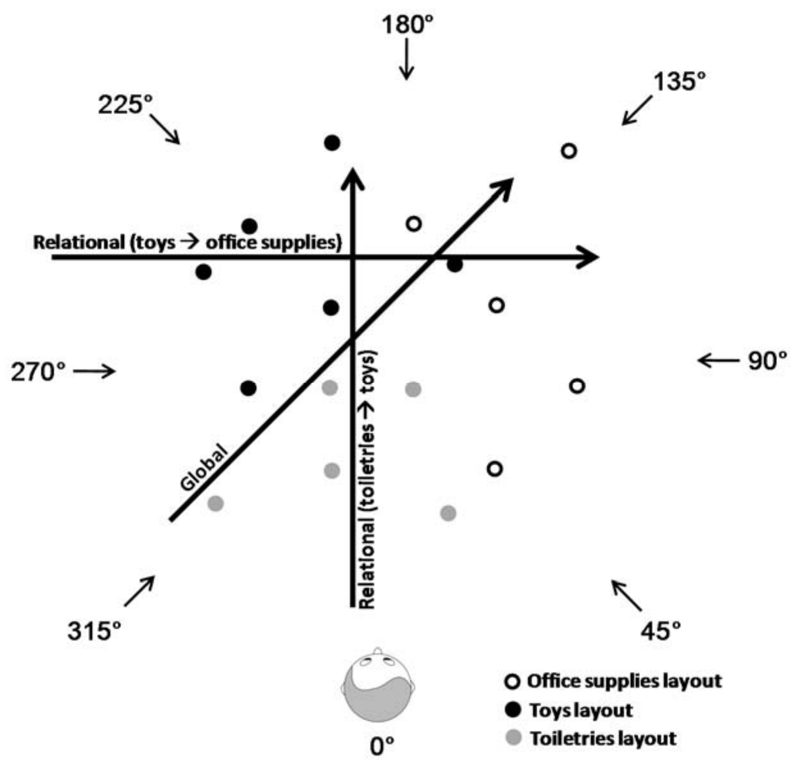

Figure 3. Object locations used in Experiment 2. Arrows represent global and relational macroaxes.

To summarize, JRD trials tested the 0 and 315° perspectives for the toiletries and toys layout pair, and the 270 and 315° perspectives for the toys and office supplies layout pair. No other imagined perspectives were tested. For each imagined perspective, six unique trials were constructed requiring correct egocentric pointing responses spaced every 45° from 0° to 315°.

Participants completed 96 JRD (two layout pairs × 2 imagined perspectives × 6 pointing directions × 4 repetitions). JRD procedures were otherwise identical to Experiment 1.

The primary independent variables were layout pair (toys and office supplies or toiletries and toys) and imagined perspective (aligned with the relational or global macroaxis). The primary dependent variable was absolute pointing error. Response time was also recorded.

Procedure. Procedures were nearly identical to the separate aligned condition in Experiment 1, with the exception that participants learned three instead of two layouts of objects. Participants were instructed to learn the toys layout first, then the office supplies layout, and then the toiletries layout. For each layout participants were instructed to learn the objects along the 0° axis.

Results

There was no evidence of speed-accuracy tradeoff. The within-participant correlation between error and latency was significantly positive (M=0.45, SE=0.09), $t(30)=5.16$, $p<.001$. As with Experiment 1, the focus is on pointing error and pointing latency results are included as Supplemental Material.

Absolute pointing error is shown in Figure 4 as a function of layout pair (toys and office supplies or toiletries and toys) and imagined perspective (aligned with the relational macroaxis or aligned with the global macroaxis). When participants made judgments between the toys and office supplies layouts, performance was best when imagining the perspective aligned with the global macroaxis. However, when making judgments between the toiletries and toys layouts, performance was best when imagining the perspective aligned with the relational macroaxis. These conclusions were supported by statistical analyses.

Absolute pointing error was analyzed in a repeated measures ANOVA with terms for layout pair and imagined perspective. A significant main effect of layout pair, $F(1,30)=27.63$, $p<.001$, $\eta_p^2=.48$, was qualified by a significant interaction between layout pair and imagined perspective, $F(1,30)=37.29$, $p<.001$, $\eta_p^2=.554$. Paired t-tests comparing imagined perspectives aligned with the relational and global macroaxes were significant for the toys and office supplies layout pair, $t(30)=2.38$, $p=.024$, and also for the toiletries and toys layout pair, $t(30)=10.69$, $p<.001$.

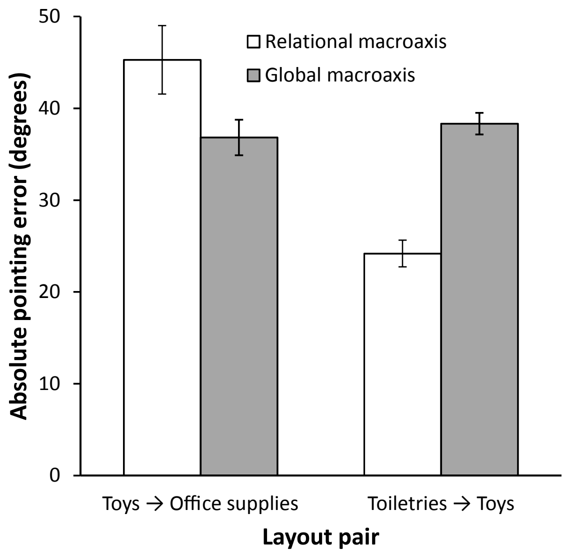

Figure 4. Pointing error in Experiment 2 as a function of perspective alignment with relational and global macroaxes and the layout pair tested. Error bars represent +/- 1 SEM.

Discussion

Contrary to expectations, neither the global macroaxis nor the relational macroaxis singularly predicted reference frame selection. Rather, reference frame selection reflected an interaction between those macroaxes and the arrangement of the layout pair. Whereas the relational macroaxis was used to represent two layouts when it was aligned with the study view, the global macroaxis was used to represent two layouts whose relational macroaxis was misaligned with the study view. One possible explanation for this finding is that the alignment of the relational macroaxis with the study view made it the most salient axis to represent the relationship between the toiletries and toys layouts. In contrast, the relational macroaxis between the toys and office supplies layouts was misaligned with the study view, rendering it less salient than the global macroaxis. Notably both relational macroaxes were aligned with the surrounding room walls, but only one was aligned with the learning view. Performance when imagining the perspective aligned with the global macroaxis was in between that of the two relational macroaxes, which makes it likely that the learning view played a critical role in creating the observed pattern.

A possible alternative interpretation of the Experiment 2 data is that participants represented the set of all objects using a macroreference frame aligned with the 0° study view, and that perspective-taking performance was negatively affected by the magnitude of deviation from that reference frame (the global macroaxis deviated by 45° and the relational macroaxis between toys and office supplies deviated by 90°). Although this interpretation cannot be ruled out without data from a broader set of imagined perspectives, it is inconsistent with results from Greenauer and Waller (2010) and Experiment 1 showing that reference frame selection is influenced by macroaxes and not by the studied view. It is also inconsistent with the current data, as reference frames are often indicated by superior performance for perspectives parallel and orthogonal to the reference direction (e.g., Mou & McNamara, 2002). Thus, a global macroreference frame aligned with the 0° study view might also produce facilitated performance when imagining the 270° perspective (see the between-layout data from the combined condition in Experiment 1), but this pattern was not evident in the data.

General Discussion

The current project makes three primary contributions to research on macroreference frames in spatial memory. First, Experiment 1 results indicate that macroreference frames characterize overlapping spatial layouts, whereas past research was limited to discrete spatial layouts. Second, Experiment 1 results show that macroreference frames are used even when the microreference frames are aligned with one another. Third, Experiment 2 indicates that macroreference frame selection depends on an interaction between the global macroaxis, relational macroaxis, and the learning view.

In previous research, when asked to recall locations within a city, residents recalled locations in clusters that could be discrete or overlapping (Hirtle & Jonides, 1985). Whereas past research on macroreference frames only employed discrete spatial layouts, the current finding that macroreference frames characterize overlapping spatial layouts lends credence to the idea that macroreference frames apply broadly to spaces learned under more naturalistic conditions.

In the present study, it was predicted that macroreference frames would only characterize situations in which the underlying microreference frames were misaligned with one another. Contrary to predictions, the separate aligned condition in Experiment 1 revealed that even aligned microreference frames can result in selection of a macroreference frame that is misaligned with the microreference frames.

When learning locations from a single view, the reference frame is typically selected from that view unless otherwise instructed (Kelly, Costabile, & Cherep, in press; Mou & McNamara, 2002; Street & Wang, 2014) or if the layout is highly symmetric and orthogonal (Richard & Waller, 2013). In contrast, macroreference frame selection in Experiment 1 occurred without actually experiencing a macroaxis-aligned view. It is therefore possible that macroreference frame selection operates on somewhat different principles compared to reference frame selection when learning just one layout. Although the global macroaxis used in the current studies was symmetric and orthogonal, those features were insufficient to cause adoption of a non-egocentric reference frame in the combined condition of Experiment 1. However, the combined condition is not a perfect control condition since the experimenter verbally emphasized that participants should learn the layout along the study view axis. A follow-up study in which participants are given no instruction except to learn the objects as a single layout would help to evaluate whether the layout used in the current studies was sufficient to induce spontaneous adoption of a reference frame misaligned with the study view.

Research on reference frame selection when learning a single layout points to an interaction between environmental axes (e.g., symmetry axes of the layout or the surrounding room) and the studied view, such that reference frame selection often occurs from a studied view aligned with a salient axis (Galati & Avraamides, 2015; Kelly & McNamara, 2008; Shelton & McNamara, 2001). Furthermore, it would be valuable for future work on macroreference frame selection to examine the effects of alignment with environmental cues and the studied view to determine the extent to which research on reference frame selection applies to macroreference frames. For example, is macroreference frame selection affected by alignment of the macroaxis with environmental structures such as room walls or with egocentric cues defined by the participant's experienced views? These questions could be answered through experiments in which the participant experiences multiple views of the scene, some aligned and some misaligned with the global macroaxis and/or surrounding room axes.

To summarize, these results indicate that macroreference frames 1) characterize overlapping spatial layouts, 2) are unaffected by microreference frame alignment, and 3) are selected on the basis of global macroaxes defined by all studied locations as well as relational macroaxes defined by subsets of locations.

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“Selection of macroreference frames in spatial memory”

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Supplemental results

Experiment 1 response latency results

Pointing latency (Supplemental Figure S1) was analyzed in a mixed-model ANOVA with terms for imagined perspective (0, 45, 90, 135, 180, 225, 270, and 315°), layout (toys, office supplies, and between layouts), and learning condition (combined, separate aligned, and separate misaligned). Significant main effects of imagined perspective, $F(7,315)=4.78$, $p<.001$, $\eta_p^2=.10$, and layout, $F(2,90)=16.03$, $p<.001$, $\eta_p^2=.26$, were qualified by an interaction between imagined perspective and layout, $F(14,630)=1.83$, $p=.032$, $\eta_p^2=.13$. This interaction appeared to be driven by a tendency for judgments about the toys and office supplies layouts to produce superior performance when imagining the 0° perspective and orthogonal perspectives, contrasted with a reversal of this pattern for between-layout judgments. No other effects were statistically significant.

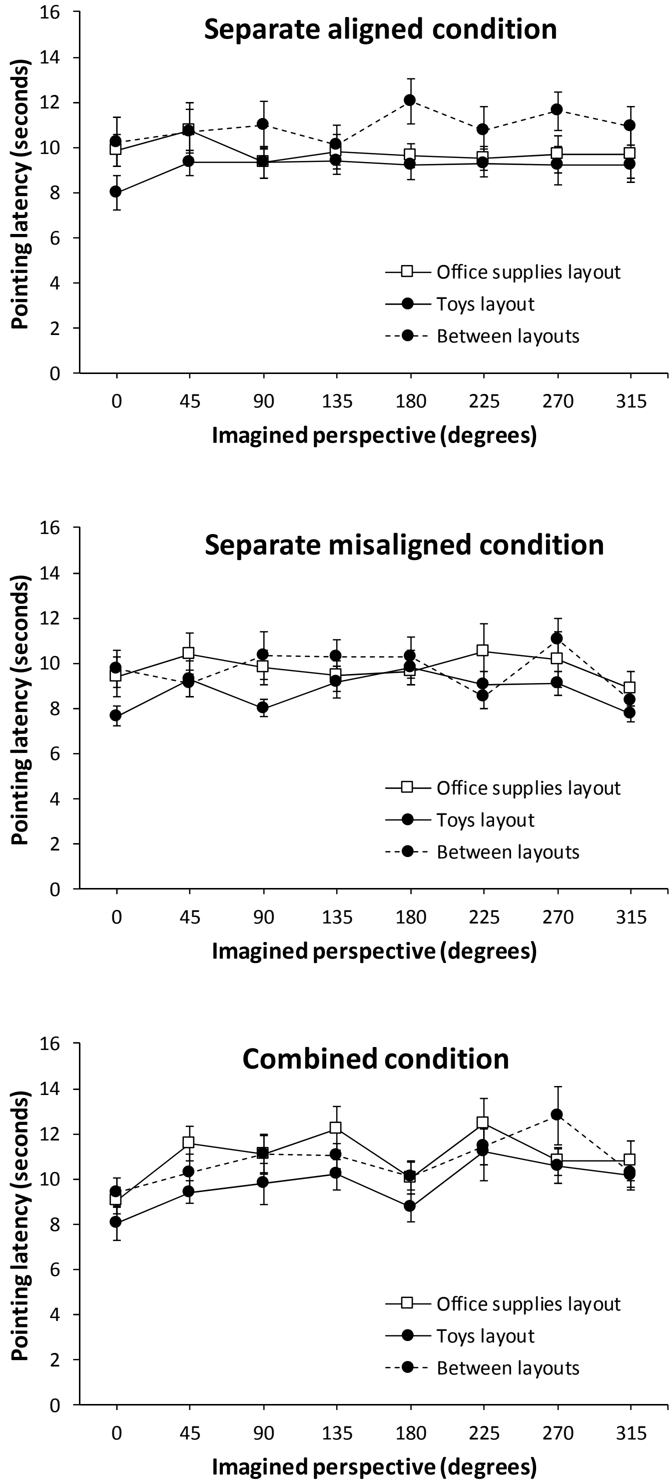

Figure S1. Response latency in Experiment 1 as a function of imagined perspective. Error bars represent +/- 1 SEM.

Experiment 1 analysis of individual differences

Follow-up analyses were conducted to further evaluate why participants in the separate misaligned condition did not represent the toys layout using a reference frame organized around the instructed perspective (315°), and specifically whether there were individual differences in success at adopting the instructed reference frame. Participants in the separate misaligned condition were subdivided into two groups based on whether they performed better at retrieving the toys layout from the 315° instructed perspective (6 participants) or the 0° studied perspective (11 participants). As can be seen in Figure S2, the two groups produce different data patterns when retrieving the toys layout (as they should, since the groups were formed on this basis). However, they did not differ in any other statistically significant way. A 2 (toys reference frame group: 0 reference frame vs. 315 reference frame) by 8 (imagined perspective) ANOVA was conducted using absolute error data, separately for each judgment type. For the toys layout, only the interaction between reference frame group and perspective was significant, $F(7,105)=3.94$, $p=.001$, $\eta_p^2=.21$, and the main effects of perspective and reference frame group were not significant. For the office supplies layout, the main effect of perspective was significant, $F(7,105)=5.31$, $p<.001$, $\eta_p^2=.26$, but the main effect of reference frame group was not significant, nor was the interaction. For between-layout judgments, the main effect of perspective was significant, $F(7,105)=3.56$, $p=.002$, $\eta_p^2=.19$, but the main effect of reference frame group was not significant, nor was the interaction.

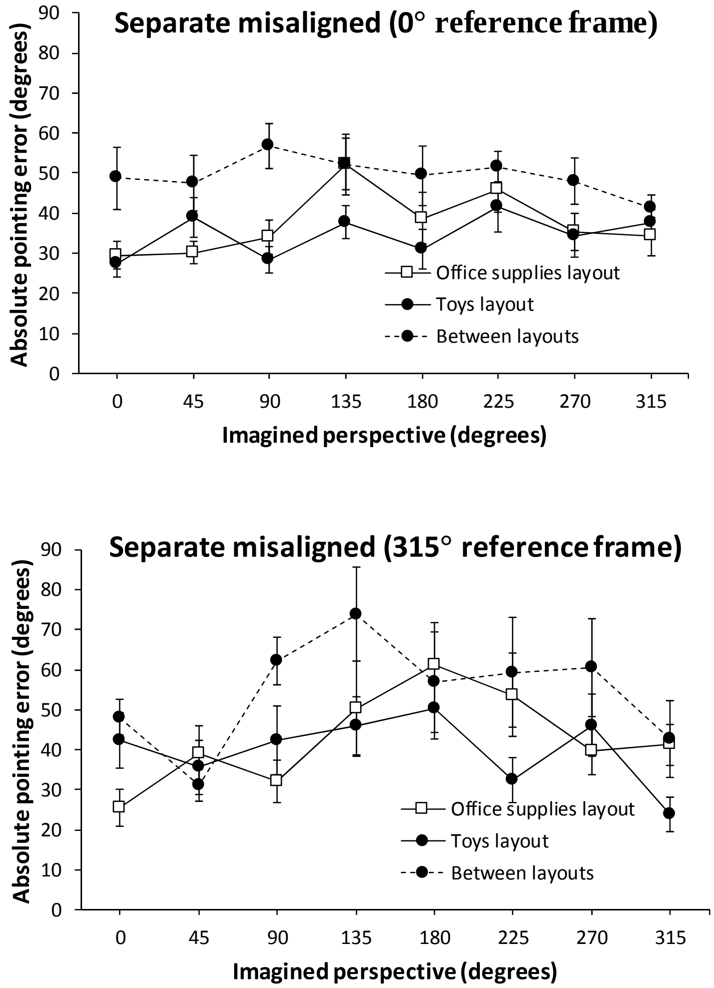

Figure S2. Pointing error in the separate misaligned condition of Experiment 1 as a function of imagined perspective and layout. Top panel shows data from participants who performed better when imagining the toys layout from 0° compared to 315°. Bottom panel shows data from participants who performed better when imagining the toys layout from 315° compared to 0°. Error bars represent +/- 1 SEM.

Experiment 2 response latency results

Pointing latency (Supplemental Figure S3) was analyzed in a repeated measures ANOVA with terms for layout pair (toys and office supplies or toiletries and toys) and imagined perspective (aligned with the relational macroaxis or aligned with the global macroaxis). A significant main effect of layout pair, $F(1,30)=10.75$, $p=.003$, $\eta_p^2=.26$, was qualified by a significant interaction between layout pair and imagined perspective, $F(1,30)=12.12$, $p=.002$, $\eta_p^2=.29$. The paired comparison between imagined perspectives aligned with the relational and global macroaxes was significant for the toiletries and toys layout pair, $t(30)=3.02$, p=.005, but not for the toys and office supplies layout pair.

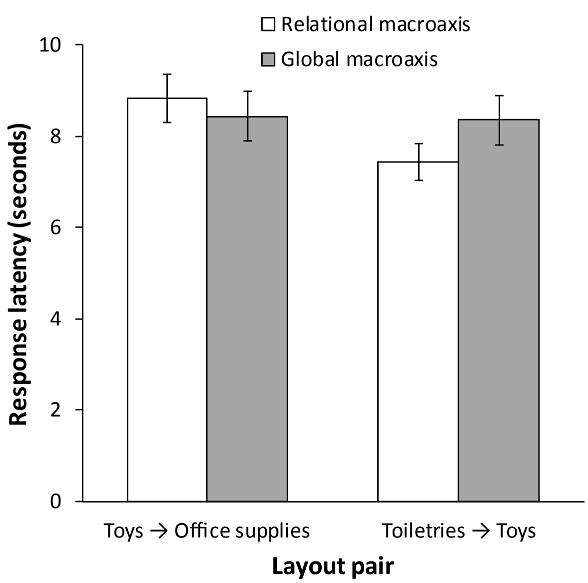

Figure S3. Response latency in Experiment 2 as a function of perspective alignment with relational and global macroaxes and the layout pair tested. Error bars represent +/- 1 SEM.